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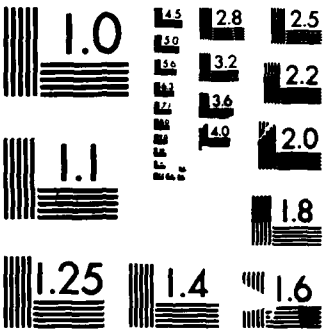

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Final Report

DISPERSION STRENGTHENING

Contract No. N00014-85-K-0058
Work No. 4311689

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INTRODUCTION

This report is a summation of the research accomplishments from 1973 to 1987 with contract No. N00014-85-K-0058. The purpose of this program was to develop a fundamental understanding of the role of finely dispersed second phase particles upon the properties of crystalline solids. Considering that the addition of a dispersed second phase is a common strengthening method, it is surprising to note the lack of information concerning the role of the dispersed second phase on physical and mechanical properties in two phase structures, e.g., heterogeneous nucleation kinetics and phase transformations. The goal of this research program was to enhance the application and development of high strength engineering alloys through achieving a better understanding of the role of dispersed second phases. The scope of this work has been directed towards studying the strengthening behavior of nickel-base superalloys, the strengthening behavior of ferrous martensite, and the kinetics of the austenite to martensite transformation. These studies have focused on the fundamental aspects of these two-phase systems that appear to control the structural characteristics and the mechanical response of these important classes of engineering materials. The following sections will describe the significant results determined during this research grant.

RESEARCH UNDERTAKEN DURING THIS PROGRAM

During the duration of this research program, the areas of research and their significant results can be presented as follows:

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1. Dispersion Strengthening

a. Nickel-base Superalloys: Nickel-base superalloys are commonly used in high temperature applications due to the strength derived from the precipitation of a coherent, ordered phase, γ'. The strength due to precipitation is attributed to the lattice mismatch between the precipitate and the matrix, the fault energy of the precipitate and the volume fraction of the precipitate. Nickel-base superalloys can be broadly categorized into 1) low volume fraction γ' (1-6%), 2) medium volume fraction γ (20-30%) and 3) high volume fraction γ containing alloys.

In this investigation, a series of 13 alloys based on the Ni-15Cr-Ti-Al-Mo base composition was used. The volume fraction of γ' in these alloys was about 20-30%. The alloys selected were designed to vary the coherency strain, the antiphase boundary energy, and the volume fraction of γ'. The γ-γ' mismatch was measured over the temperature range 25 to 800°C. The flow stress of each alloy in the peak aged condition was determined, and the contribution due to precipitation was evaluated over the temperature range 600 to 800°C.

The incremental yield strength due to precipitation was determined by subtracting the solid solution yield strength from the yield strength of the peak aged two phase alloy. Normalization of the yield strength was obtained by dividing the yield strength due to precipitation by the square root of the weight fraction of γ'. Low mismatch alloys show very little variation in the γ-γ' mismatch with temperature. The normalized increment in the yield strength for these alloys did not show any correlation with the γ-γ' mismatch. High coherency strain alloys also did not show any

correlation between the normalized increment in the yield strength and the gamma-gamma prime mismatch. This leads one to conclude that coherency strain is not a dominant strengthening mechanism in nickel-base superalloys with low volume fractions of γ'. The important conclusions developed from this work are:

1. The coherency strain decreased with increasing temperature. Variations in coherency strain were found to have little influence on the steady-state creep rate. However, large γ-γ' mismatch induced agglomeration and coalescence of the γ' precipitate during creep at half the melting temperature.
2. An increment in the flow stress, when normalized by the weight fraction of γ', is linearly correlated to the γ-γ' mismatch existing at a temperature within the 25 to 800^{o}C temperature range. In alloys with high lattice mismatch, the correlation was particularly strong regardless of the antiphase boundary energy.
3. The weight fraction of γ' is a major factor controlling the steady-state creep behavior of the Ni-15Cr-Al-Ti-Mo alloy series. Increasing the fraction of γ' decreased the steady state creep rate.
4. Variations in coherency strain were found to have minimal influence on the steady state creep rate. The steady

state creep rate was found to depend on the weight fraction of γ'. Increasing the weight fraction γ' decreases the steady state creep rate.

5. Dislocation-precipitation interactions during tensile deformation were studied for high and low coherency alloys. In high coherency alloys, the γ' particles were bypassed by dislocations, whereas in low coherency alloys, the γ particles were sheared during tensile tests. It is also interesting that the macroscopic yield behavior did not show any variation from the particle bypass to particle shear failure mode. In creep deformation of low coherency alloys, intrinsic /extrinsic stacking fault shear of γ particles were also observed.
6. In contrast with previous literature on nickel-base superalloys with low γ volume fractions, coherency strain does not contribute to the strengthening mechanism. Order strengthening appears to be the strongest contributor to the strengthening associated with γ' precipitation in these nickel base superalloys.
7. A multiple regression equation was developed to correlate the lattice parameters of gamma and gamma prime to the alloy chemistry on Ni-15Cr-Ti-Al-Mo alloys. The equations can be stated as follows:

$$a_{\gamma} = 3.5238 + 0.00165\ Cr + 0.00509\ Mo + 0.00184\ Ti$$

$a_o\ \gamma' = 3.5610 + 0.00030\ Cr + 0.00093\ Mo + 0.00731\ Ti$

where the unit of the lattice parameter is angstroms and the chemical concentrations are in atomic percent. Good correlation between experimental and empirical results have been observed.

8. A similar linear regression equation was developed to relate the thermal expansion coefficient of γ and γ' to the alloy chemistry. This equation can be state as:

$$\alpha^{\gamma} = (14.6456 - 0.389256\ Mo + 0.269907\ Al + 0.338253\ Ti)\ x10^{-6}$$

$$\alpha^{\gamma'} = (14.2606 - 0.182603\ Mo - 0.043648\ Al - 0.278344\ Ti)\ x10^{-6}$$

where the unit of the thermal expansion coefficient is in./^{o}C and the chemical concentrations are in atomic percent. These equations are useful in predicting the γ-γ' mismatch at high temperatures.

9. In Ni-21Cr-Al-Mo alloys with 4 at.% Al, no precipitation occurs at 760^{o}C.
10. The increase in yield strength due to precipitation is linearly dependent upon the weight fraction of precipitate when the precipitate-lattice mismatch is held constant.
11. Coherency effects dominate the low temperature mechanical

behavior for these alloys at constant weight fraction precipitate. Two independent methods of varying mismatch, one at constant Ti/Al ratio (constant precipitate fault energy) and one with varying Ti/Al ratio (varying fault energy) resulted in a linear correlation of the normalized yield stress increment with coherency strain.

12. The stress dependence of the steady-state creep rate, as represented by the stress exponent, n, was found to fall in the range n = 3 to 5 for the experimental nickel-base alloy series. The creep stress exponent was observed to be sensitive to γ' particle size for the coherency strain alloys. For these alloys, increasing the γ' particle size lowered the stress exponent. Little influence of γ' particle size was found for the high coherency strain alloys.

This work was the completion of the masters thesis of M. Naik and the doctoral theses of R.G. Miller and D.A. Grose.

Work has also been performed on dispersion strengthened Ni-thoria alloys. In this work, Ni-thoria samples were first loaded, then brought to test temperature under rapid heating conditions (greater than $1000^{o}C$/sec) and then creep tested. Under these stress and rapid thermal local conitions, elliptical voids formed at the nickel-thoria interface. The unusual aspect of these voids was that the major axis of the elliptical voids was normal to the loading direction.

A model was developed to predict the shape change of voids present in

the microstructure. The model predicts the shape change and the angular dependence of the major axis of the ellipse. Similar models can be developed for any void as long as the mean normal stress is known. Peculiarly, if thermal shock did not first rupturethe particle-matrix interface and first form the circular void, as in slowly heated specimens, vacancy flux during creep is away from the matrix thoria interface and no void would form. With interface rupture as a result of thermal shock, the vacancy flux is in the opposite direction to the interface, causing void growth with a spatial variation. The conclusions drawn from this investigation are:

1. A model utilizing the mean normal stress about a circular hole in an elastic solid can be used to predict the behavior of the more complicated three-dimensional problem.
2. Stress assisted vacancy diffusion is responsible for the shape change observed in the voids surrounding thoria particles.
3. The stress assisted vacancy diffusion and the related shape change of the void surrounding the thoria particles predicted by the model agrees in detail with the experimentally observed phenomena.

This work was completed in the masters thesis of R. Maxwell.

b. Dispersion Strengthened Ferrous Alloys: A series of dispersion strengthened Fe-Ni alloys were designed to permit evaluation of the relative effects of M_s temperature, chemical driving force, and austenite yield

strength on resultant martensite morphology without altering matrix chemistry. Using a carefully selected lath forming Fe-27Ni-0.25C base alloy, incremental additions of yttrium oxide dispersion enable a decrease in the M_S to the morphology transition, an increase in the thermodynamic driving force at the M_S to above the morphological transition value, and an increase in the austenite yield strength to above the morphological transition value. The results and conclusions of this investigation may summarized as follows:

1. An addition of 2 vol.% yttrium oxide dispersion coupled with an austenite grain size from 100 to 2 microns, depresses the M_S temperature from 66 to -25^{o}C.
2. At the lowest austenization temperature of 600^{o}C, dispersion strengthening was sufficient to induce a shift in morphology while holding constant matrix chemistry and thermal history.
3. During the course of the morphological transition, an intermediate morphology, "internally twinned lath" martensite, was observed. Lath-like character included the formation of parallel bands with no retained austenite. Analysis showed that alternate crystals exhibit internal twinning and possess an apparent habit plane of $(225)_a$, i.e., characters typically associated with plate martensite.
4. Previous correlations of thermodynamic driving force and austenite yield strength with martensite morphology have been shown to break down. Lath martensite was observed at an

austenite yield strength of over 50 ksi and a thermodynamic driving force of 350 cal/mol. which is well in excess of previously reported transition values for the Fe-Ni alloys.

5. The transition to plate martensite occurred in an M_s temperature range of -2 to -25°C. This agrees with the value of the transition range of M_s temperature in Fe-Ni alloys.

This work was incorporated in the doctoral research of P. Brofman.

2. Martensite Strength and Transformation

During this program, a sequence of research projects were designed with an aim towards determining the relationships between process history, alloy effects and austenite properties upon the strength and transformation kinetics of martensitic alloys. During the contract, the most significant results were:

a. Transformation Kinetics and Alloy Effects: The transformation rate from austenite to martensite (% transformed/C) for athermal, lath type steels was shown to be dependent on two composition dependent variables. They are the rate of change of chemical free energy with temperature and the energy expended in plastically deforming the austenite surrounding a growing martensite embryo in order to accommodate the transformation volume and shear strains. These results clarify what had previously been confusing results from other investigations where only one of these two composition dependent variables were considered. On the basis of the work completed during this research program, all these results can now be generalized in terms of a single model. This work was presented in the doctoral thesis of R. Pradhan.

Measurements of the effects of different alloying elements in iron on the volume strain associated with the austenite to martensite transformation found that the volume expansion accompanying the martensite phase transformation at the M_S temperature is the summation of two factors. The "temperature factor" contribution of an element is positive for any element that lowers the M_S temperature (C, Mn, Ni, Cr, and Mo), zero for an element that has no effect on the M_S temperature (Si), and negative for an element that raises the M_S temperature (Co). The "lattice parameter" contribution is positive for austenite stabilizing elements (C, Mn, Ni, Cr, and Mo), negative for gamma loop forming elements (Mo and Si), and nearly zero for an element that is a gamma loop former but also expands the austenite phase field (Cr).

Individual effects of carbon, manganese, nickel, chromium, molybdenum, silicon, and cobalt on the volume expansion were measured in five Fe-C and twenty five Fe-C-X alloys. Additions of carbon, manganese, nickel, and chromium increased the volume expansion; cobalt and molybdenum had little effect; and silicon additions decreased the volume expansion at the M_S temperature. These individual effects were added to produce an empirical equation relating the volume expansion at the M_S temperature to chemical composition. Values for the volume expansion predicted by this equation were found to be in reasonable agreement with experimentally measured values for six Fe-C-X-Y alloys.

Silicon and possibly molybdenum alloying additions reduced the volume expansion at the M_S temperature of Fe-C-X alloys, supporting prior observations linking these alloying elements to a reduced incidence of quench

cracking in steels. Since cobalt plus nickel additions to ferrous alloys also lessen the severity of quench cracking in steels. This work was completed in the doctoral thesis of J. Moyer.

b. Quench Rate Effects: Rapid quench rate experiments (10^3 to 10^5 ^oC/min.) were performed to study the effect of carbon segregation in the austenite, autotempering and room temperature aging on the overall strength of several ferrous martensites. Concurrently, the nature and the size of the carbide particles as a function of quench rate in the transformed martensite were studied using low angle x-ray scattering. The results of this completed study are as follows:

1. The as quenched hardness and carbide or carbon segregate particle size for high M_s temperature alloys showed a decreasing trend with increasing quench rate.
2. Aging at room temperature (20^oC) for short times eliminated any apparent effects of quench rate on the hardness and particle size.
3. The variation in the as quenched particle size and hardness with quench rate occurs only within the same range of quench rates where the M_s temperature was previously reported to increase with increasing quench rate.
4. Data in this project indicated no correlation between quench rate and autotempering.
5. Carbon diffusion continues during autotempering and room temperature aging, and increases the hardness of the

martensite.

6. Rapid quench rate does not have any long-term effect on the martensite hardness. The hardness of the slow and fast quenched specimens recover to an equal level after sufficient aging at room temperature.
7. In the fully aged condition, the average carbide particle size was the same for the specimens quenched at different cooling rates.

The procedure and results of this work has been presented in the masters theses of V.J. Sharma and D. Hennessy.

c. Elastic Strain-Transformation Interactions: There is considerable indirect evidence of the interaction of elastic strainand the martensite phase transformation in metals. Unfortunately, however, such evidence is based upon the application of bulk values of strain imposed upon poly-crystalline specimens, while the transformation is followed by gross characteristics such as $M_s$temperature or the volume transformed. In order to determine these effects in more detail, and particularly to explore the nature of the transformation process, we have studied of the effects of pure shear strain upon the transformation kinetics and morphology of single crystal,thermoelastic martensite. A Cu-Zn-Al alloy, with an $M_s = 20^oC$ was selected for this study. Data from this study indicated that the M_s temperature, the martensite morphology and the hysteresis losses (M_s, M_f, A_s and A_f) are each sensitive to changes in the application of shear stresses as low as 0.05 percent of the proof stress in this alloy system.

The effect of shear stress upon the M_s temperature was pronounced, and measured to 8.547^{o}K per Kg/mm^2. From the Clausius-Claperon equation together with the stress sensitivity of the Ms, the entropy was calculated to be 0.378 cal/mol^{o}K. Using differential scanning calorimetry, the measured enthalphy of the transformation was 99.4 cal/mol. From the equilibrium temperature, $T_o = 1/2(M_s + A_f) = 254^{o}$K, the entropy was determined to be 0.398 cal/mol^{o}K. This is in good agreement with the results obtained from the stress sensitivity measurements.

A theoretical model of the transformation behavior of this alloy system has also been derived. The unique aspect of the model is the assumption that the control of the plate growth is the thermoelastic equilibrium between chemical-free energy and the elastic energy in the local region adjacent to the transformation interface. The consideration of localized strain rather than overall equilibrium elastic energy controlling the growth kinetics is unique in the understanding of thermoelastic transformations. In particular, we explain for the first time, the experimental observations of thermoelastic radial plate growth as well as thermoelastic plate thickening. Previous models were forced to postulate that upon nucleation, radial plate growth occurred spontaneously until meeting strong barriers, e.g., grain boundaries, then plate thickening occurred thermoelastically.

This theoretical model further explains the hysteresis behavior in thermoelastic martensites. The theory shows that the hysteresis of the transformation cycle comes from the friction of the interphase boundary motion and that the frictional energy consists of two components which can be classified as frictional enthalpy and frictional entropy. The frictional

entropy is shown to determine the gap on the hysteresis curve between the cooling and heating components of the curve. The frictional enthalpy determines the slope difference, i.e., the difference of the transformation rates for the kinetic curves of cooling and of heating. This study was completed in the doctoral thesis of H.Deng.

d. Thermal-Elastic Transformation Substructure: There has been considerable research in the area of reversible, thermal elastic martensite transformations. However, little effort has been directed towards the hysteresis behavior and substructure development associated with large numbers of cycles through the transformation.

During this contract, the effect of thermal cycling between the M_f and A_f on the thermal hysteresis, temperature dependence, and the morphology of the martensitic transformation in the Cu-ZnAl alloy was completed. The hysteresis behavior of the cyclic transformation, as characterized by following the change in electrical resistivity accompanying the transformation changed in two respects. First, the M_s and A_f temperatures shifted to higher temperatures while the M_f and A_s temperature remained constant. Secondly, the amount of martensite undergoing cyclic transformation decreased. These changes appeared to saturate at 300 cycles and could be partly recovered during room temperature aging. The morphology and mode of transformation also changed. During the first few cycles, transformation occurred in two simultaneous ways: 1) as martensite plates which are observed to grow and thicken in a continuous manner and 2) as plates which form in a "burst" process. After sixty cycles,no "burst" type transformation occurred during cooling and plate growth and thickening was stepwise. This work was

completed by a visiting scholar, J. C. Li.

e) Elastic Modulus Effect: The mechanical properties of ferrous martensites, particularly those that affect engineering application such as ductility and fatique, are sensitive to the specific martensite morphology present. While the prevailing viewpoint has been that martensite morphology is controlled by the carbon content and M_s temperature, research carried out under this contract has shown that quench rate, chemical driving force, and austenite yield strength can affect the resulting morphology. Morphology transitions without altering the matrix chemistry suggests the existence of an anisotropic decrease in the martensite shear modulus during cooling, which would affect the shears that occur during the transformation. The anisotropic decrease in the austenite elastic constants alters the resulting active shear system and as a result could control the resulting martensite morphology. Anisotropic modulus relaxation during the martensitic transformation has been confirmed by many researchers for alloys with small atomic displacements such as occur in non-ferrous alloy systems. Specific ferrous alloys, which have large atomic displacements during the martensite transformation have been shown, in this contract, to exhibit anisotropic modulus relaxation in polycrystalline samples. Ultrasonic testing was used to accurately measure the temperature dependence of the elastic properties of the austenite parent phase for polycrystalline ferrous samples. The observation of the conditions required for Zener lattice softening in textured polycrystalline samples and not in untextured polycrystalline specimens was observed in the doctoral research of R.E. Maxwell and is justification for continued ultrasonic research on single crystalline samples. This insensitivity of the

polycrystalline results can be attributed to grain boundary scattering and grain orientation effects.

In single crystal research, the existence of a strong anisotropic modulus relaxation in the austenite phase just prior to the transformation to martensite has been observed in ferrous alloys which exhibit the plate morphology. Ferrous single crystals which transform in the mixed lath/plate morphology showed a weak anisotropic modulus relaxation effect and ferrous single crystals which transform in the lath morphology did not exhibit this modulus relaxation. The observation of the modulus relaxation condition is a characteristic common in nonferrous martensites which exhibit soft mode transformations, such as CuZnAl alloys, and has been confirmed during this contract.

A martensite nucleation model for ferrous alloys has been proposed during this contract. Ferrous martensites forming in the plate morphology show the conditions required for Zener lattice softening and the lattice instability model. In the lattice instability theory, a phonon pulse or lattice wave is generated from individual atom vibrations. As the phonon pulse interacts with a stable austenite atom structure at the M_s temperature, the atoms rearrange to form a configuration energetically favorable for the martensite transformation to occur. The additional energy required to cause a ferrous alloy, a large displacement transformation, to react in the same mechanism as a nonferrous alloys, small displacement transformation, can be related to the premartensitic effect resulting from a ferromagnetic to paramagnetic transition near the M_s temperature.

In ferrous alloys which transform in the lath morphology, the insensi-

tivity of the elastic properties to modulus relaxation indicates that the classical thermodynamic theory best models lath martensite nucleation. In the classical thermodynamic nucleation model, a interaction between chemical free energy, the elastic energy, the interfacial energy, and the energy caused by external forces occurs. When the energy balance of the system is pushed into a nonequilibrium condition, the martensite phase transformation occurs.

In ferrous alloys which transform in the mixed lath/plate morphology, a competitive combination of both the lattice instability theory and the classical nucleation theory appears to apply. Ultrasonic elastic property measurements, attenuation measurements, differential scanning calorimetry, resistivity, and dilation measurements were used to support this interpretation.

Orientation effects have also been evaluated during this program. In this work, single crystals oriented with faces on the (100) and (110) planes have been studied. It has been observed that the (110) plane shows a greater sensitivity to modulus relaxation. This has developed an interest in determining the single crystal elastic properties of the parent phase austenite in the martensite growth directions and in the austenite growth directions. The following trends have been observed:

1. In the austenite and martensite growth directions, the parent phase austenite exhibiting plate and mixed lath/plate mormorphologies showed C_{11} decreasing as a function of decreasing temperature until a transition in lattice stability occurs. At the lattice instability transition, C_{11} increases

until the M_s temperature is reached.

2. In the austenite and martensite growth directions, the parent phase austenite exhibiting lath morphology showed a continual decrease in C_{11} with decreasing temperature.
3. In the austenite and martensite growth directions, the parent phase austenite exhibiting plate morphology showed an increase in C_{44} as a function of decreasing temperature until a premartensitic lattice transition caused C_{44} to decrease. A decreasing single crystal shear elastic constant is an indication of Zener lattice softening.
4. In the austenite and martensite growth directions, the parent phase austenite exhibiting lath and mixed lath/plate morphologies show a decrease in C_{44} as a function of de- decreasing temperature and an increase in C_{44} just prior to the M_s temperature.
5. In the martensite growth direction, the parent phase austenite exhibiting the plate morphology shows the greatest change in C_{11} prior to the M_s temperature at 0.90×10^{12} dynes/cm^2.
6. In the austenite growth direction, the parent phase austenite exhibiting the plate morphology shows the greatest change in C_{44} prior to the M_s temperature at 0.55×10^{12} dynes/cm^2.

This work will be presented in the doctoral thesis of C. Tomonto.

TECHNICAL REPORTS

During the duration of this research program, the following papers and talks have been presented at scientific meeting, submitted for publication, or have been published.

1. Papers:

1. "The Effect of Quench Rate on the Properties and Morphology of Ferrous Martensite",by S.J. Donachie and G.S. Ansell, Metallurgical Transactions, 6A, 1863, October 1975.

2. The Effect of Quench Rate on the Properties and Morphology of Ferrous Martensite",by S.J. Donchie and G.S Ansell, Technical Report No. 5, ONR Contract No. N00014-67-A-0117-0011 NR 031-689/9-17-70, March 1975.

3. "The Volume Expansion Accompanying the Martensite Transformation in Iron-Carbon Alloys", by J. Moyer and G.S. Ansell, Metallurgical Transactions, 6A, 1785, Sept. 1975.

4. "The Volume Expansion Accompanying the Martensite Transformation in Iron-Carbon Alloys", by J. Moyer and G.S Ansell, Technical Report No. 6, ONR Contract No. N00014-67-A-0117-0011 NR 031-689/9-17-70 031-689/9-17-70 (471), June 1975.

5. "Kinetics of the Martensite Transformation in Athermal Fe-C-Ni-Cr Alloys" by R. Pradhan and G.S. Ansell, published in the Proceedings of the International Conference on "Martensitic Transformations", Kiev,U.S.S.R.,May 1977. and Metallurgical Transactions, Vol. 9A, 793, June 1978.

6. "Kinetics of the Martensite Transformation in Athermal Fe-C-Ni-Cr Alloys", by R Pradhan and G.S. Ansell, Technical Report No. 7, ONR Contract No. N00014-76-C-0458 NR031-689/10-21-75 (471) July 1976.

7. "The Relationship Between Austenite Strength and the Transformation to Martensite in Fe-10Ni-0.6C Alloys", by T.J. Nichol, G. Judd and G.S. Ansell; Metallurgical Transactions, Vol. 8A, 1877, December 1977.

8. "The Relationship Between Austenite Strength and the Transformation to Martensite in Fe-10Ni-0.6C Alloys", by T.J. Nichol, G. Judd and G.S. Ansell; Technical Report No. 8, ONR Contract No. N00014-76-C-0458-NR031-689/10-21-75(471) July 1977.

9. "Low Temperature Mechanical Behavior of Ni-15Cr-Al-Ti-Mo Alloys", by R.G. Miller and G.S. Ansell, Metallurgical Transactions, Vol. 8A, December 1977.

10. "Low Temperature Mechanical Behavior of Ni-15Cr-Al-Ti-Mo Alloys", by R.G. Miller and G.S. Ansell, Technical Report No. 9, ONR Contract No. N00014-76-C-0458-NR031-689/10-21-75(471), February 10, 1978.

11. "Kinetics of the Martensitic Transformation in Athermal Fe-C-Ni-Cr Alloys", Technical Report No.10, ONR Contract No. N00014-76-C-0458-NR031-689/10/21-77(471), January 1979.

12. "The Influence of Coherency Strain on the Elevated Temperature Tensile Behavior of Ni-15Cr-Al-Ti-Mo Alloys", by D.A. Grose and G.S. Ansell, Metallurgical Transactions, Vol. 12A, Sept. 1981.

13. "The Influence of Coherency Strain on the Elevated Temperature Tensile Behavior of Ni-15Cr-Al-Ti-Mo Alloys", by D.A. Grose and G.S. Ansell, Technical Report No. 11, ONR Contract No. N00014-67-A-0177-0001.

14. "Effect of Austenite Strength on the Transformation to Martensite in Fe-Ni and Fe-Ni-C Alloys", G.S. Ansell, P.J. Brofman, and T.J. Nichol, Proceedings of the International Conference on Martensitic Transformations, Cambridge, MA,24-29, June 1979, pp. 350-355 (published 1980.)

15. "The Effect of Fine Grain Size on the Martensitic Transformation in Fe-Ni and Fe-Ni-C Alloys", by P.J. Brofman and G.S. Ansell, Metallurgical Transactions.

16. "On the Morphology of Martensite in Fe-27Ni Alloys", by P.J. Brofman and G.S. Ansell, Proceedings , Conference on Phase Transformations, Pittsburgh, PA, August 1981.

17. "On the Morphology of Martensite in Fe-27Ni Alloys", P.J. Brofman and G.S. Ansell, Technical Report No. 12, ONR Contract No. N00014-67-A-0177-0001., 1981.

18. "The Effect of an Inert Oxide Particle Dispersion on the Morphology of Martensite in Fe-27Ni-0.025C Alloys", by P.J. Brofman and G.S. Ansell, Metallurgical Transaction A, p.203, February 1982.

19. "The Effect of Thermal Cycling on the Thermoelastic Martensitic Transformation in a Cu-Zn-Al Alloy", by J.C. Li and G.S.Ansell, Metallurgical Transactions A, Vol. 14A, p.1293, July 1983.

20. "The Effect of Thermal Cycling on the Thermoelastic Martensitic Transformation in a Cu-Zn-Al Alloy", by J.C. Li and G.S. Ansell, Technical Report No. 13, ONR Contract No. N00014-67-A-0177-0001 , 1983.

21. "Tempering Kinetics of Alloy Steels as a Function of Quench Rate and M_s Temperature", by D.G. Hennessy, V.J. Sharma and G.S. Ansell, Metallurgical Transactions A, Vol. 14A, p.1013, June 1983.

22. "Tempering Kinetics of Alloy Steels as a Function of Quench Rate and M_s Temperature", by D.G. Hennessy, V.J. Sharma and G.S. Ansell, Technical Report No. 14, ONR Contract No. N00014-67-A-0177-0001.,1983.

23. "On the Effect of Grain Size on the M_s Temperature in Fe-27Ni-0.025C Alloys", by P.J. Brofman and G.S. Ansell, Metallurgical Transaction A, Vol. 14A, p. 1929, September 1983.

24. "On the Effect of Grain Size on the M_s Temperature in Fe-27Ni-0.025C Alloys", P.J. Brofman and G.S. Ansell, Technical Report No.15, ONR Contract No. N00014-67-A-0177-0001.,1983.

25. "Effect of Refractory Elements on the Coherency Strain and Flow Stress of Nickel-Base Superalloys, by M. Naik and G.S. Ansell, 1984 ASM Conference on Refractory Elements in Superalloys-Effects and Availability, ASM, Metals Park, Ohio, 1984.

26. "Effect of Refractory Elements on the Coherency Strain and Flow Stress of Nickel-Base Superalloys, by M. Naik and G.S. Ansell, Technical Report No. 16, ONR Contract No. N00014-67-A-0177-0001, 1984.

2.Presentations:

1. Detroit Section, AIME, Invited Seminar, March 1973, "Ferrous Martensite".

2. Spring Meeting, AIME-IMD, June 1973,paper, "The SD-Effect in Maraging Steels".

3. Union Carbide Research Center, Invited Lecture, June 1973, "The Strength and Transformation of Ferrous Martensite".

4. American Metal Climax Corp. Research Center, Invited Lecture, August 1973, "Alloy Effects on the Volume Strain Attendant to the Austenite to Martensite Transformation".

5. Third International Conference on the Strength of Metals and

Alloys,Cambridge, England, August 1973, paper "The Particle-Matrix Interface Strength in TD-Nichrome".

6. Seminar-Powder Metallurgy 73, Invited Lecture, October 1973, Minsk, USSR, "The Effect of Interface Strength on the Properties of Dispersion-Strengthed Alloys".

7. Kalinin Polytechnic Institute, Invited Lecture, October 1973, Leningrad, USSR, "The Influence of the Particle-Matrix Interface Strength on the Properties of Oxide-Dispersion Strengthened Alloys".

8. The Institute for Steel and Alloys, Invited Lecture, October 1973, Moscow, USSR, "The Influence of the Particle-Matrix Interface Strength on the Properties of Oxide-Dispersion Strengthened Alloys".

9. University of California, Berkeley, March 1974, Invited Seminar, "The Strength and Transformation of Ferrous Martensite".

10. Conference on Martensite, Invited Lecture, April 1975, Massachusetts Institute of Technology,"Processing Effects on the Structure and Properties of Ferrous Martensite".

11. "The Relationship Between Austenite Strength and the Transformation to Martensite in Fe-10Ni-0.6C Alloys", presented at the Annual Meeting of the AIME, Atlanta, Georgia (March 1977).

12. "Low Temperature Mechanical Behavior of Ni-15Cr-Al-Ti-Mo Alloys", presented at the Annual Meeting of the AIME, Atlanta, Georgia (March 1977).

13. "Kinetics of the Martensite Transformation in Athermal Fe-C-Ni-Cr Alloys", presented at the International Conference on Martensitic Transformations, Kiev, U.S.S.R. (May 1977).

14. "Mechanical Alloying and Precipitation Hardening," Seminar at the Powder Metallurgy Institute, Beyellorussian Polytechnic Institute, Minsk, U.S.S.R.,(May 1977).

15. "The Effect of Fine Grain Size on the Martensitic Transformation in Fe-Ni and Fe-Ni-C Alloys", Joint U.S./Japan Seminar on the Mechanical Behavior of Metals and Alloys Associated with Displacive Phase Transformations, Rensselaer Polytechnic Institute, Troy, N.Y., June 1979.

16. "Effect of Austenite Strength on the Transformation to Martensite in Fe-Ni and Fe-Ni-C Alloys", International Conference on Martensitic Transformations", M.I.T., Cambridge, Mass., June 1979.

17. "Strengthening Mechanisms in Martensitic Steels", Peking University Institute for Iron and Steel Technology, Peking, China, July 1979.

18. "Tempering Kinetics of Alloy Steels as a Function of Quench Rate and Ms Temperature ," D.G. Hennessy, V.J. Sharma and G.S. Ansell, Fall Meeting, TMS AIME, Louisville, KY, October 1981.

19. "The Effect of Thermal Cycling on the Thermal Elastic Martensite Transformatiom on Cu-Zn-Al alloys," J.C. Li and G.S. Ansell, Fall Meeting, TMS AIME, Louisville, KY, October 1981.

20. "Effect of Refractory Elements on the Coherency Strain and Flow Stress of Nickel-Base Superalloys," M.Naik and G.S. Ansell, invited paper, 1984 ASM Conference on Refractory Elements in Superalloys, Araxa, Brazil, April 6-13, 1984.

21. "The Strength and Transformation Behavior of Ferrous Martensites", G.S. Ansell, invited speaker, ASM Denver Section, October 1984.

22. "An Introduction of New Technology in Mining," G.S. Ansell, invited speaker, American Mining Congress, San Francisco, September 23, 1985.

23. "Blending New Technologies into an Established Industry", G.S. Ansell, invited speaker, Joint Meeting of the Geophysical Society of Houston and the Houston Geological Society, Houston, Tx, March 1986.

24. "An Ultrasonic Evaluation of Ferrous Martensites", C.V. Tomonto, presented at: Timken Corp., Canton, Oh. (4/86); Chevron Oil Corp., Richmond, Cal. (2/86); Corning Glass Works, Elmira, N.Y. (3/86); General Electric Knoll's Atomic Power Laboratories, Schenectady, N.Y. (4/86).

PATENT APPLICATIONS:

1. Thin Insulating Film Containing a Dispersion of Conducting Particles, patent applied for April 1973.

DEGREES GRANTED:

T. Bhat, Ph.D. (1973)
T.J. Nichol, Ph.D. (1974)
J. Moyer, Ph.D. (1977)
R. Pradhan, Ph.D. (1977)
R.F.Miller, Ph.D. (1978)
M.W. Broadley, M.S. (1979)

D.A. Grose, Ph.D. (1980)
R. Maxwell, M.S. (1980)
V.J. Sharma, M.S. (1980)
P. Brofman, Ph.D. (1981)
D. Hennessy, M.S. (1982)
C. Tomonto, M.S. (1983)
H. Deng, Ph.D. (1984)
M. Naik, M.S. (1985)
C. Tomonto, Ph.D. candidate (to complete requirements in 9/87)

OTHER CONTRACTS:

1. Second-Phase Particles - NASA, 1973-1975.

2. Structure and Compositional Variations in Human Teeth-NIDR 1973.

3. The Influence of Austenite Process History on the Martensite Transformation - NSF, 1973-1976.

4. Welding Workshop - ONR, 1974-1975.

5. Interdisciplinary Research Center - Advanced Composite Materials NASA/AFOSR, 1976-1985.

6. Improved High Modulus Carbon Fibers, NASA, 1978-1980.

7. Soft Mode Phenomena in Iron-Nickel-Chromium Carbon Steels, NSF 1978-1981.

AWARDS:

G. S. Ansell:

1. Appointed Chairman of the National Manufacturing Studies Board of the NRC-NAE.

2. Paper entitled: "Creep of a Dispersion Hardened Aluminum Alloy" was selected as a "Citation Classic" of the Citation Index.

3. Appointed President, Colorado School of Mines.

4. Received Souzandrade Gold Medal from the Federal University of Maranhao, Brazil.

5. Appointed President, TMS/AIME, 1986.

PARTICIPANTS:

G.S. Ansell - Principal Investigator
G. Judd - Co-Principal Investigator
T. Bhat - Graduate Student
M. W. Broadley - Graduate Student
P. Brofman - Graduate Assistant
H. Deng - Graduate Assistant
D. A. Grose - Graduate Student
D. Hennessey - Graduate Assistant
R. Maxwell - Graduate Assistant
R. F. Miller - Graduate Student
J. Moyer - Graduate Student
M. Naik - Graduate Assistant
T. J. Nichol - Graduate Student
R. Pradhan - Graduate Student
V. J. Sharma - Graduate Student
C. Tomonto - Graduate Assistant
J. C. Li - Visiting Scholar
R. Heitman - Undergraduate Assistant
H. Giguere - Undergraduate Assistant

END

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